Quantum Feedback in Cavity QED and Quantum Nanomechanics

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As experimental technology continues to improve, the idea of actively manipulating microscale quantum processes—rather than just merely observing them—is rapidly gaining ground and, indeed, already being demonstrated. As a result of these advances, it is expected that sooner or later quantum technologies of quite some complexity will exist. It is important to note that all classical complex engineered systems make essential use of feedback control in their operation. The question arises whether some form of quantum feedback control is available to be applied to future quantum technologies and, if so, how different is it from its classical counterpart?

A quantum feedback control block diagram looks very similar to its classical counterpart (Fig. 1). The output from a detector is sensed in order to control the parameters of the Hamiltonian and thereby affect changes in the output, if needed. While the basic principles are the same, there are several key differences. Classically, the more one can know about the system, the better off one is with regard to predicting the system behavior and hence in being able to control it. Quantum mechanically, however, due to the existence of measurement backaction one has to be careful in designing how the measurements are carried out, as the very act of measurement can render the future behavior of some quantity to be controlled, more, not less, uncertain. In addition, approaching the quantum limit is difficult in terms of keeping the system sufficiently isolated from external disturbances and the implementation and design of ideal quantum detectors remains an open issue. Finally, the actual control implementation requires significantly more computation than compared to classical feedback.

Our work in quantum feedback control has covered not only important theoretical aspects [1], but also realistic implementation scenarios in cavity quantum electrodynamics QED [2] and nanomechanics experiments [3]. In both of the latter, we have focused on the question of whether a quantum system can be cooled to its ground state, or very near to it, using quantum feedback methods.

In the cavity QED experiments, an atom is trapped in an optical microcavity in the strong-coupling regime, and the output laser light is monitored via homodyne detection. The resulting photocurrent provides information about the position of the atom in the cavity, which, in turn can be used to cool the atom by varying the intensity of the driving laser field. One of the key

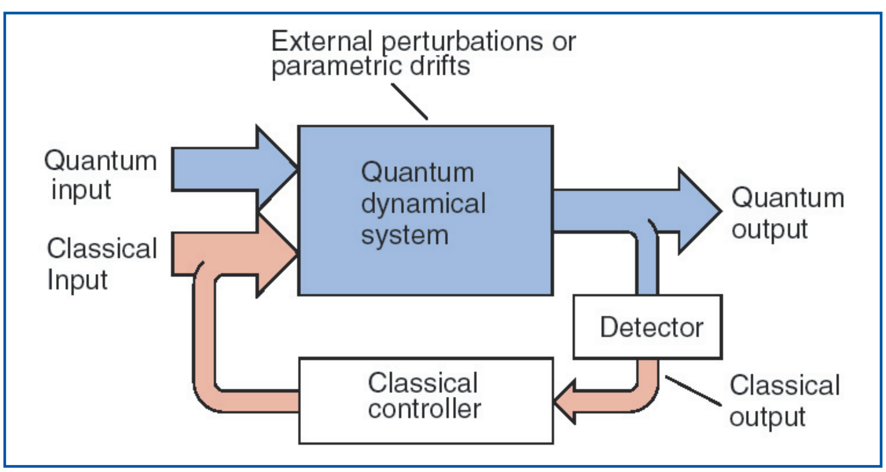

Figure 1—
Schematic of a quantum feedback control system.

results in this work is the demonstration that a simplified Gaussian estimator provides very good cooling performance (Fig. 2). Because the feedback can only be applied in a symmetric way, the state cools to an equal mixture of the ground and first excited state. But, at this point, spectroscopic techniques can be used to cool to the ground state. Detailed calculations to fully understand the behavior of this system are ongoing on parallel supercomputers at Los Alamos National Laboratory.

Nanoresonator technology has reached the point that resonators are now being built that are less than a factor of 10 away from the quantum limit. The quantum limit is reached when the thermal energy is less than the ground state energy of the resonator. To achieve this, one could either lower the resonator temperature to mK, or increase its frequency, which in turn increases the ground state energy. It turns out that lower frequency resonators are much easier to deal with experimentally (lower losses, better measurement coupling), thus, if possible, it would be preferable to cool the resonator below temperatures achievable with a dilution refrigerator. We have proposed a feedback cooling scheme based around a single-electron transistor used as a position sensor for the resonator, with a feedback signal applied via a control electrode (Fig. 3). These devices have been built in Keith Schwab's laboratory at the Laboratory for Physical Sciences (LPS), Maryland. Successful feedback cooling has been demonstrated but has not yet led to a quantum-limited resonator.

[1] A.C. Doherty, S. Habib, K. Jacobs, H. Mabuchi, and S.M. Tan, *Phys. Rev. A* **62**, 012105 (2000).
[2] D.A. Steck, K. Jacobs, H. Mabuchi, T. Bhattacharya, and S. Habib, *Phys. Rev. Lett.* **92**, 223004 (2004).
[3] A. Hopkins, K. Jacobs, S. Habib, and K. Schwab, *Phys. Rev. B* **68**, 235328 (2003).

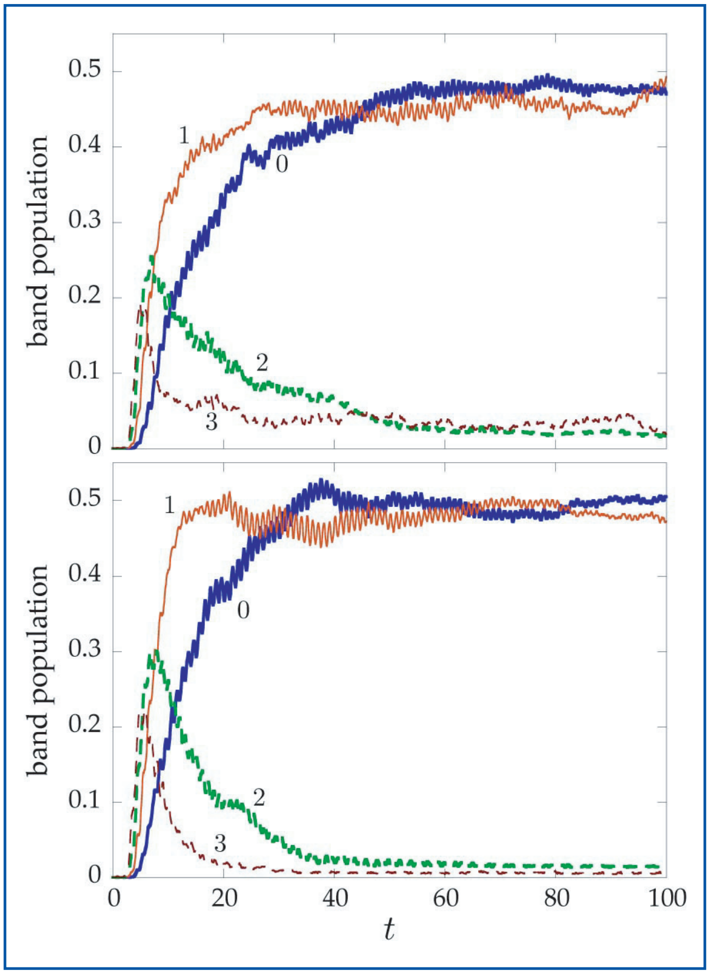

Figure 2—
Evolution of the band populations for the lowest four energy bands of the optical lattice, averaged over 128 trajectories. Top: cooling based on the Gaussian estimator. Bottom: cooling based on perfect knowledge of the actual wave function.

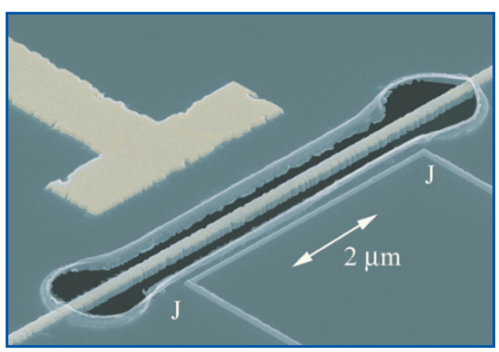

Figure 3—
A nanomechanical resonator (courtesy Keith Schwab, LPS). The thin central bar is coated with gold in order to bias it, as is the T-shaped electrode to the left. The thin line parallel to the resonator is the gate of a single-electron transistor, which serves as the quantum sensor. Feedback is applied by varying the potential on the left electrode.